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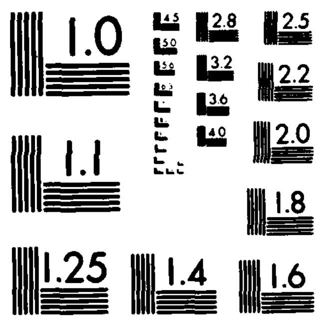

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MULTIANGULAR SCANNING ABSORPTION
TECHNIQUES FOR
THREE DIMENSIONAL
COMBUSTION DIAGNOSTICS

AD-A133 842

AFOSR 77-3439

Final Scientific Report

prepared for:
AFOSR, Bolling AFB

Attn: Dr. L. H. Caveny
September 1, 1977 - August 30, 1982

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POLLUTION	FLAMES	X-RAY	SENSORS
RADICALS	LASERS	FILTERING	TOMOGRAPHY
THREE-DIMENSIONAL			

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This program explored the potential of absorption techniques for low ppm, real time three-dimensional combustion diagnostics. Convolution, Fourier transforms and iterative algorithms have already been proven in x-ray absorption tomography and interferometric applications. They have been tested and compared for their ability to determine typical pollutant and radical concentrations as they appear in flames or exhausts. The effect of the number of scans has been analyzed for parallel beams. A satisfactory trade off was shown to exist between accuracy and the number of viewing angles. The potential of this method was

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demonstrated in the laboratory. An Argon-diluted methane jet was observed at several sections along its axis. Time-averaged two dimensional profiles were reconstructed from the absorption scans effected from six and twelve angles. The theoretically predicted dependence of the accuracy on the number of observation angles was verified for sections near the burner and far downstream. It compares well with data measured with other methods. In the last phase of activity, a laser beam was transformed into a sheet of light (slicing mode), and made to converge on a 126-element array, with electronics suitable for repeatable 1.5 KHz scanning and data processing. Available memory modules (4K) allow for 34 successive slicings of a passing target within 20 milliseconds. In this manner, a detailed projection of three dimensional flow field concentrations is available. An axisymmetrical flow (a sooty flame) has been measured and a tomographic procedure was applied to these data. Wider ranges of absorptions are being considered and multiangular experiments (non-symmetrical cases) should follow.

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RESEARCH OBJECTIVES

Recent advances in the study of large scale structures have given a detailed if qualitative description of the onset of transition. Mixing parallel flows and round jets has been studied, by Schlieren high speed movies in particular. Spanwise instabilities have been observed, which pair several times in increasingly convoluted patterns until viscous mixing takes over. The resolution of these high speed (6 KHz) measurements extends practically to the Kolmogorov scale. The existence of lengthwise, 3-dimensional instabilities has also been documented and their role in the evolution of the spanwise vortices is being investigated.

In view of these newly uncovered transitional structures, the need for quantitative real time three dimensional data is quite urgent. A method has been developed which is susceptible to deliver concentration and temperature fields at a rate of repetition of about 100 Hz. As shown in Fig. 1, a set of m parallel absorption scans taken fron n different angles can be treated mathematically to yield a mxn map of concentrations. This tomographic method, which established itself in a wide medical market (CAT Scanners), is being converted from a steady state, 2-dimensional, X-ray absorption device, to a 3-dimensional, optical diagnostics, operating in the KHz range. Thus, 3-dimensional distributions of chemical elements (soot, CO, OH,...) can be documented in real time, either in the slicing mode by a linear sensor array or in the 2-dimensional instantaneous mode by a square array (Fig. 6).

The potential of this method was demonstrated in the laboratory. An argon-diluted methane jet was observed at several sections along its axis. Time-averaged two-dimensional profiles were reconstructed from the absorption scans effected from six and twelve angles. The theoretically predicted dependence of the accuracy on the number of observation angles was verified for sections near the burner and far downstream. It compares well with data measured with other methods.

In the last phase of activity, a laser beam was transformed into a sheet of light (slicing mode, see also Fig. 6), and made to converge on a 126-element array, with electronics suitable for repeatable 1.5 KHz scanning and data processing. Available memory modules (4K) allow for 34 successive slicings of a passing target within 20 milli-seconds. In this manner. a detailed projection of three dimensional flow field concentrations is available. An axisymmetrical flow (a sooty flame) has been measured and a tomographic procedure was applied to these data. Wider ranges of absorptions are being considered and multiangular experiments (nonsymmetrical cases) should follow.

SUMMARY OF RESULTS

Over the 5 year period of this grant, the following areas of combustion tomography were investigated:

A. Reconstruction Algorithm

The retrieval of a MxN grid of concentrations from a multiangular set of MxN absorption measurements was performed with a two dimensional Fourier technique widely used if other applications (Fig. 1). The purpose of this simulations study was to establish the minimum number of angles which could reconstruct a realistic flame profile with reasonable accuracy. Ref. 1 discusses the conclusions of this theoretical phase in terms of profile characteristics, optimum filters and noise contributions. In general it was found that 10 separate angles would satisfy most requirements (Fig. 2).

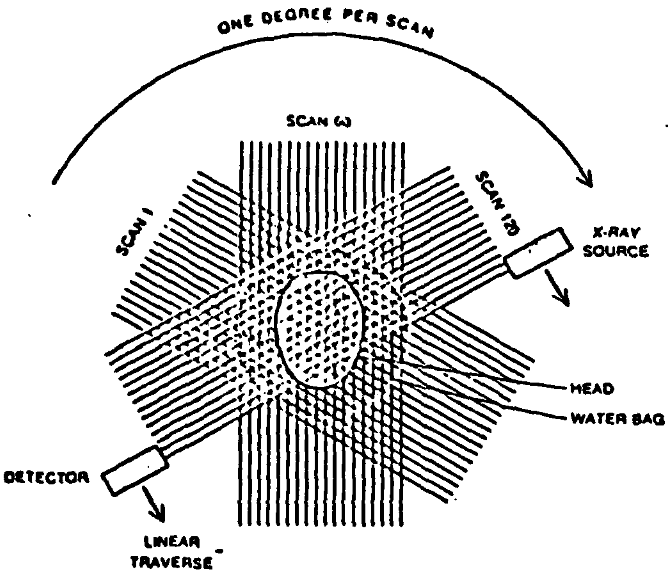


Fig. 1 - An early application of multi-angular scanning: the X-Ray CAT Scanner

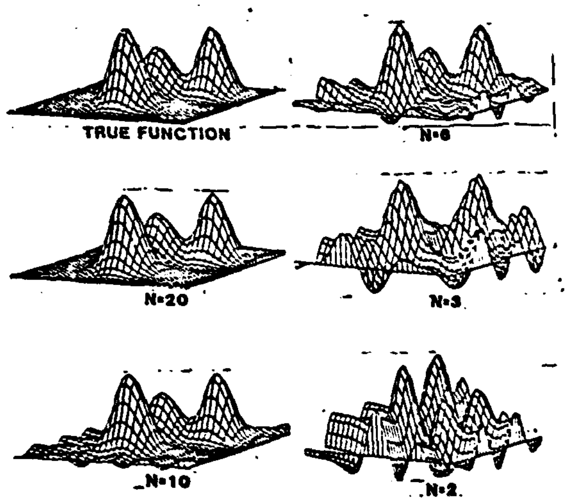


Fig. 2 - Reconstruction of 3 Gaussians from N Projections

B. Steady State Tomography

The tomographic method has been adapted to flame concentration and temperature measurements. A cooperative effort between NBS and the grantees has concentrated at first on the study of concentration distribution in a cold asymmetrical methane-argon jet (1 & 2). A steady-flow experiment was utilized as the first test case for multiangular reconstruction because of the simplicity of the required instrumentation. By rotating the jet assembly while the optics remained fixed, the multi-angular scanning of an asymmetrical function was performed (Fig. 3). Absorption by methane of the 3.39μ line of a He-Ne laser was used to determine concentration across the jet. Transmitted radiation was detected by an uncooled lead selenide (PbSe) detector. A preamplifier with a gain of ten is used to impedance-match the resulting detector output to an oscilloscope and lock-in analyzer. The resultant DC analog signal is digitized and displayed by computer graphics (Fig. 4).

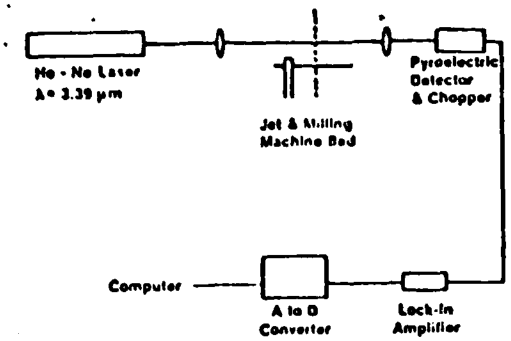


Fig. 3 - Cold Methane jet tomography. The off-center mounting of the jet requires a non-symmetrical reconstruction.

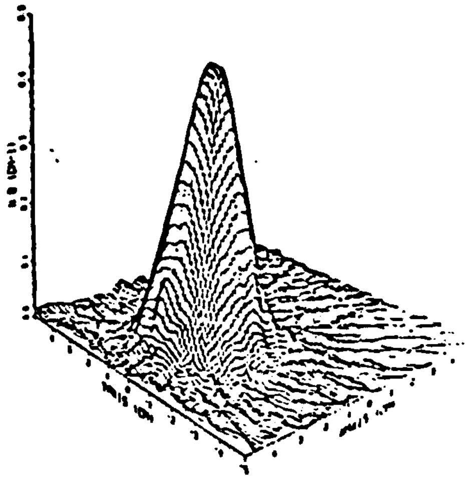


Fig. 4 - Reconstructed $N_iQ_{i\lambda}$ field in a section 10 diameters from the jet orifice.

In the present experiments a 10% CH_4 - 90% Ar mixture was used. All measurements were done under atmospheric pressure and room temperature conditions. A series of absorption measurements were taken across the jet at intervals of .64 mm (.025 inches) at three different heights above the jet exit. The jet rotated by 15^o intervals and the experiment was repeated. Data for twelve separate angles was thus obtained to map out the jet region.

These experimental results proved that good reconstruction accuracy was obtained when the modified Shepp-Logan filter was used, and a sufficient number of angles was used: twelve angles eliminate a substantial amount of the aliasing occurring with six angles only (Fig. 4). These conclusions are discussed extensively in (2).

Also a test of the method was carried out on a laminar diffusion flame (3). In general, to obtain N_i our of $N_iQ_{i\lambda}$ requires the use of several frequencies when temperature variations exist. In this particular case, earlier measurements of the temperature field were available and the need for additional frequencies was alleviated. However, a tunable laser is now available and preliminary calculations have been made: a completely experimental determination of the concentration and temperature fields is now possible.

C. High Speed Tomography

Since our work - and that of others - have shown that a limited number of angles would allow an accurate reconstruction of jet profiles, it is possible to contemplate experiments of the type illustrated in Fig. 5 where the same laser could be used to illuminate a jet simultaneously from five to ten different directions. In this manner, tomographic measurements can be made within a time interval smaller than the characteristic time of the fluid mechanic events of interest (e.g., 50 μsec for instabilities). This is accomplished readily by inserting an optoacoustic deflector in front of the CW laser. Also, it must be demonstrated that a three dimensional fluid structure, moving perpendicular to the plane of the figure, can be illuminated and the transmitted intensity I be measured at a high rate of repetition.

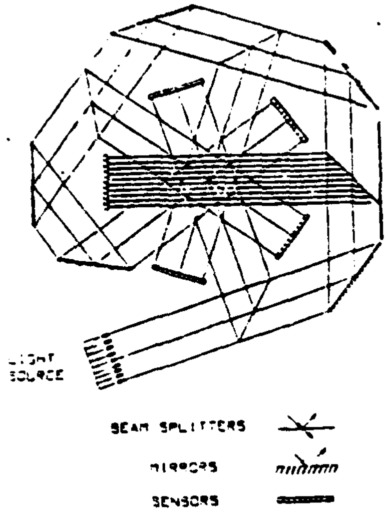


Fig. 5 - Instantaneous multiangular scanning (N=5, M=100)

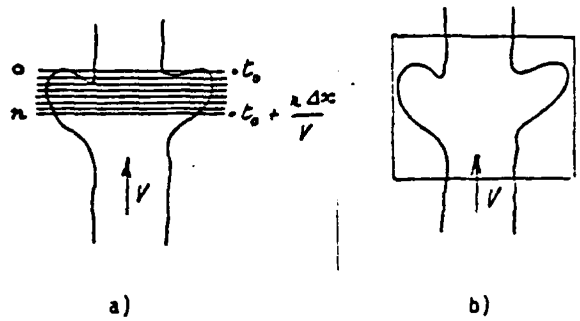


Fig. 6 - a) Linear Array Slicing, as described in the text. The velocity V is determined separately. b) An alternative approach: the "snapshot" of the passing structure by a rectangular array matrix.

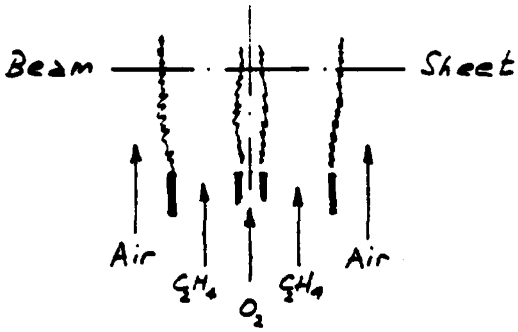
As a first step towards a multiangular real time tomographic measurement system, a single laser-sensor array have been tested at NBS. A sheet of light, fixed in space, was flashed in 50 µsec bursts, at a repetition rate of 1.5 KHz; this rate if fixed by the time necessary for the 128 element silicon sensor array to "unload" all the measured intensities into the data processing equipment. In this manner, an absorbing flow structure passing through this plane would be sliced many times in succession. The reconstruction of these parallel slices, separated by a distance corresponding to the produce (velocity x time interval), is a quasi-instantaneous 3-D map of the structure (Fig. 6). The following characteristic times have been achieved to date for the simple detector system:

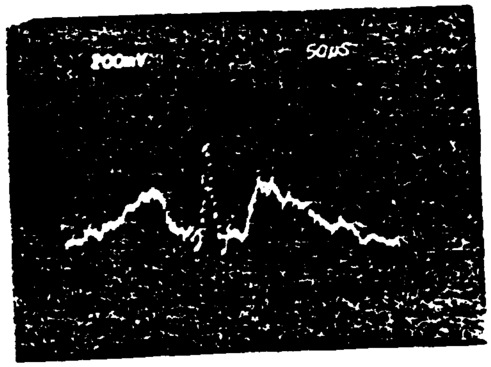
a) The optoacoustic deflector (20 KHz) provides 50 µsec which illuminates the target with only 1/10 mm blur on a 2m/sec jet.

b) the 128 element array can be shifted at 1.5 KHz as the absorbing jet structure flows by. At 2m/sec, the structure can be chopped every 1.3 mm: thus, a one centimeter long jet structure can be displayed as a set of 7 layered concentration maps.

c) the 4K memory can store the output of 32 consecutive slices of 128 readings each. Thus a continuous viewing time of 32/1.5 ≈ 20 milliseconds is available. At 2m/sec, a 4 cm long jet section can be displayed.

The temporal and spatial resolution capabilities of the system have recently been demonstrated on a sooty flame. In these experiments, injection of either oxygen or nitrogen was used to moderate the soot particle field with a modulation frequency of 250 Hz. (Figs. 7 and 8)





Figs. 7 and 8 - 250 Hz pulses of oxygen axially injected, generating a sooty, light absorbing interface.

D. Beam Steering

A closer examination of Fig. 8 and of the corresponding digitized data indicates an increase of intensity outside the flame, when the flame is activated. This anomaly is possibly due to the refraction of the laser beam by the temperature gradient field near the flame front. We have pursued a theoretical study of this phenomena and we were testing, by contract end, an inversion algorithm which would correct the intensity readings for this phenomena (Ref. 4).

Also related to this work is the organization at GWU of a small diagnostics laboratory where such beam steering will be measured on typical flames. The testing of this facility was effected with a Rayleigh thermometry project (Ref. 5) which emphasized noise control.

E. Conclusion

It can be appreciated from this section that much is yet to be done to develop combustion tomography into a reliable, tested diagnostic technique. The inclusion of some form of frequency scanning (temperature) into an already rapid sequence of array measurements, the collection, storage and processing of large quantities of data, problems associated with temperature gradients (beam steering) ..., such are some of the difficult tasks on the road ahead.

However, these difficulties are not conceptual blocks. At worst, they will demand more time and money. It seems fair to argue that that long lead time in the development of this technique has to do with the completeness of its answer: "real time" three dimensional profiles. In view of the strong need expressed in current turbulence research for such "deterministic" information, even more efforts should be exerted in this promising area of diagnostics.

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LIST OF PERSONNEL

Robert Goulard, Professor	16 man-months
Philip J. Emmerman, Research Associate	12 man-months
Graduate Research Assistants	30 man-months

Parts B and C of the experimental work reported above were performed at the National Bureau of Standards with their own support. Drs. Semerjian and Santoro are the main investigators.

INTERACTION

Most of the papers listed in the list of publications were given at the corresponding professional meetings. Lively discussions were exprienced on each occasion. Attendance at other meetings and contractor's reviews have also generated active discussions regarding this new technique.

SPECIFIC APPLICATIONS OF THE RESEARCH

Three-dimensional absorption diagnostics by multiangular scanning have been demonstrated with complete success in such commerical applications as medical X-ray tomography and materials testing. An important new step would consist of making this technique applicable to <u>dynamic</u> situations, where real time histories of non-steady phenomena would be recorded. Heart and lung motion, liquid boiling, plasma dynamics, cloud evolution, combustion fluidized beds are examples which come to mind. Especially promising is the three dimensional time history of coherent structures in transitional jet mixing.

It is also important to note that the experience gained in tomographic reconstruction will be applicable to all other path-integrated diagnostics (e.g., holography). In particular the correction of beam steering,apath integration of refraction indices, is applicable to <u>all</u> combustion diagnostics.